

EXHIBIT DX1

TO DECLARATION OF PETER J. GOSS IN
SUPPORT OF DEFENDANTS' MOTION TO
EXCLUDE THE OPINIONS AND TESTIMONY OF
GARY SETTLES, PH.D.

G. S. Settles

Schlieren and Shadowgraph Techniques

Visualizing Phenomena
in Transparent Media

With 208 Figures and 48 Color Plates

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1 Historical Background

...it would open not only a cranney, but a large window...into the Shop of Nature, whereby we might be enabled to see both the tools and operators, and the very manner of the operation itself of Nature...

Robert Hooke, Observation LVIII, Micrographia

When I discover something new it has a musty smell, as if it hadn't been opened since the world began.

Buckminster Fuller

It has been on my mind for years to tell the history of schlieren and shadowgraph techniques in detail and proper chronological order. This story reveals a connection generally unappreciated amongst the works of several well-known fathers of technology and others not so well-known, at least not in this context. It is the story of a way of seeing the invisible, and of discoveries centuries before their time; discoveries that nonetheless eventually played an important role in far-flung branches of science and technology. Other elements of this history touch on the key role of direct observation and the almost-lost art of ingenious bench-top experiments in physics. Despite beginnings centuries ago, only now can a complete history be written – thanks in large part to the scholarship of several colleagues who have a fine appreciation of history [11-13].

1.1 The 17th Century

The father of the optics of inhomogeneous media is the great enigmatic Robert Hooke (1635-1703) [14]. Destined to remain forever in Newton's shadow, Hooke was nevertheless a surpassing experimental genius in his own right. He observed both the microscopic world and the heavens, discovered and named the cell, fathered the field of elasticity, and made basic contributions to physics, chemistry, meteorology, geology, and biology [15]. Yet Hooke remains faceless to us, since no likeness of him survives [16].

Hooke's contributions of present interest came during his most productive years [14], when he was simultaneously involved with microscopy, telescoping, glass technology, and optical shop testing [17-19], all of which are closely related to the

present topic. These multifarious endeavors, along with his fascination with atmospheric refraction, led him to establish the optics of inhomogeneous media as a new field of scientific endeavor.

Hooke described this new field in his famous *Micrographia* [17], Observation LVIII, which is a thorough and cogent discussion of light refraction due to density variations in the atmosphere and in liquids. With this background he explained a great many phenomena: the twinkling of stars, convection in fluids, "heat haze," turbulent mixing and eddies, chromatic aberration, stratified flows, hydrostatics, and mirages. Even the modern field of gradient-index optics [20] was presaged. Key among these observations was that of veins (streaks, striae, *schlieren*) in glass.

Hooke's first schlieren method was the direct observation of a thermal air disturbance against a distant light-dark boundary: "...you shall find such a tremulation and wavering of the remote object, as will very much offend your eye" [17]. This unaided visual observation of schlieren effects, in which the pupil of the eye cuts off refracted rays, was not formally recognized as a schlieren technique for three centuries [2]. However, it must have been observed by our curious ancestors even many centuries before Hooke.

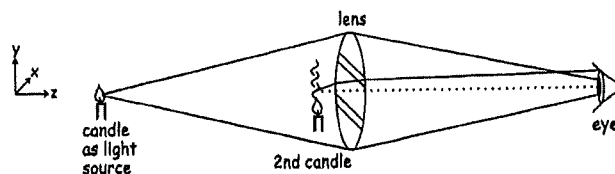


Fig. 1.1. Hooke's original schlieren system, using two candles, a lens, and the human eye.

But, being the premier instrument-maker of his time, Hooke next devised a much better schlieren method [14,21]. He replaced the distant light-dark boundary with the image of a candle flame, projected by a concave mirror or lens upon the pupil of the eye. As shown in Fig. 1.1, this illuminates the entire diameter of the lens to the eye of the observer. A second candle flame, now placed near the lens, refracts some light rays so strongly that they fall outside the pupil and are blocked, thereby revealing the transparent convective plume of the candle through changes in light intensity seen by the eye. Hooke understood this completely, and even diagrammed the refraction of the candle plume in *Micrographia*. Thus began a long, close relationship between the new method of schlieren observation and the ancient candle.

Images from a modern reenactment of this experiment are shown in Figs. 1.2a-b. A lens or mirror with a focal length on the order of 1 m or more is required to see the schlieren effect clearly. Such long-focus optics were, in fact, being ground for telescopes in Hooke's day [17]. A simple candle flame still makes a usable schlieren light source even today – as effective for this experiment as any modern source and better than most lasers.

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Hooke went on to point out, almost casually, that the convective plume of a lit candle can also be seen by way of its shadow, as cast by the Sun on white paper [14,22]. He was describing what we now know as the shadowgraph technique, usually attributed to V. Dvorák in 1880 [23]. Two photos from a reenactment of this original shadowgraph experiment are shown in Fig. 1.3. It is such a simple physics experiment that almost everyone has seen it in one form or another, but Hooke was the first to explain it.

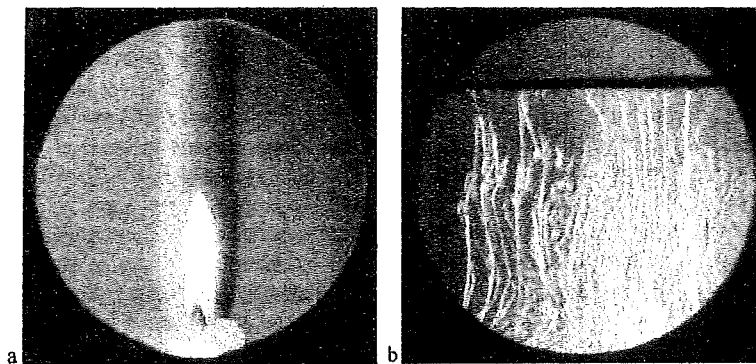


Fig. 1.2. Images from a reenactment of Hooke's schlieren demonstrations before the Royal Society: a candle plume, b dissolution of "sal-nitre" in water. Photos by author.



Fig. 1.3. Images from a reenactment of Hooke's original shadowgraph observation, showing the convective plume of a candle in shadows cast by sunlight. Photos by author.

Hooke saw the role of scientific instruments as an extension of human perceptions [24] – in this case to see the invisible. His descriptions of optical refraction [17], the convective plume of a candle [21], and the function of his new visualization techniques are all quite accurate, even by today's standards. But the pressure of his position as curator of experiments for the Royal Society caused him to leave

many fruitful topics only partially explored. He shared this weakness with Aristotle and Leonardo: a technical "butterfly syndrome" that caused him to flit from one fascinating topic to another while seldom completing the study of any [15]. A full account of his optical works was promised for a book called *Dioptricks* that, alas, he never wrote.

Hooke's effect on many technical fields was thus more catalytic than comprehensive [25]. And so it was that the optics of inhomogeneous media, like several of his other discoveries, suffered the fate of being forgotten in his time, rediscovered centuries later, and attributed to others.

From today's perspective it is not surprising that the schlieren technique arose naturally in the early days of microscopy, telescopic and glass technology. It is curious, though, that no one pursued it after it was demonstrated several times by Hooke, circa 1672, to dozens of members of the Royal Society. Here lay the key to unseen worlds, like those of the microscope or the heavens. Had Hooke's lead been followed in the 17th Century, the course of science and technology would have been altered. For one thing, we would not use the term *schlieren* today. (Hooke [22] called his new technique "the way of the concave speculum.")

On the other hand, there was little immediate need for optical flow visualization in the 17th Century. It would not be crucial for ballistics until Victorian times, not for high-speed flight until after World War I. This may help explain the apparent lost opportunity. Robert Hooke discovered much that was novel, that would arise of necessity only centuries later. Once can understand, then, that some of it was overlooked in his day. The schlieren technique was but one of these orphans of genius, a classic example of an idea centuries before its time.

Only about a decade after Hooke's work, Christiaan Huygens (1629-1695) also invented a version of the schlieren technique using a distant light-dark boundary [26]. Huygens is now famous, of course, for his astronomical discoveries, time measurement, kinetic energy formula, and a key optical principle named for him (Sect. A.2.2). He used the schlieren technique to look for striae (*veines du verre*) in glass blanks prior to grinding lenses from them. He also re-invented Hooke's candle-illuminated schlieren technique for similar purposes [14,26]. This approach is part of what we now call *optical shop testing*, a field originated by Huygens, but not generally attributed to him.

1.2 The 18th Century

After Huygens, the thread of the optics of inhomogeneous media is almost lost until the 19th Century, but for one man. The sole known contribution during the 18th Century comes from a most-unlikely source: Marat.

Jean Paul Marat (1743-1793) is remembered as a notorious character of the French Revolution. He is almost forgotten as a physician and scientist, and a key biographer [27] devotes but a few pages to this aspect of his life. Nevertheless in 1780, nine years before the Revolution, Marat published a volume on the physics of fire [28] that contains – apparently – the first optical flow visualization image

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Fig. 1.4.
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ever printed. Shown here in Fig. 1.4a, it is indisputably a shadowgram. A candle flame is flanked by the thermal plumes of heated metal objects. As in Fig. 1.3 the warm air, less dense than the ambient, refracts light outward to form a bright fringe around an inner, darker zone. The laminar candle plume is handsomely drawn in its transition to turbulence. This key observation entered the fluid dynamics mainstream only when officially discovered by Osborne Reynolds a century later.

What can be said here of such a man as Marat? Some biographers discredit his scientific work and label him a charlatan [27]. Asimov [29] blames him for the guillotine death of Lavoisier, in revenge for his rejection of Marat's "foolish homegrown notions on the nature of fire." Conner [30], on the other hand, argues convincingly for the legitimacy of Marat's scientific work.

In any case, Marat's strong account of his Sun-powered shadowgraph projector [28] – he called it a "helioscope" – is certainly convincing. His shadowgrams are a key precedent: since Hooke published no shadowgrams, Marat's are evidently the historical first of their kind.

In the strangest turn of all, the French Academy of Sciences sent a delegation accompanied by Benjamin Franklin to visit Marat's laboratory [30]. With characteristic jocularly, Franklin thrust his bald head into Marat's shadowgraph beam and, sure enough, a rising thermal plume was seen by all (see Sect. 9.4.2). Marat falsely interpreted what he saw, though, as evidence of "igneous fluid."

Eventually Marat's experiments were rejected by the scientific establishment, whereupon he became alienated from it. At the onset of the Revolution his medicine was replaced by radical politics, his fire research by fiery oratory. Marat found the glory he sought as "The Friend of the People," the champion of the poor, the scourge of nobility, and a symbol of boundless revolutionary zeal. On his account the guillotine-blade fell until the streets ran red with blood.

Centuries later we are still ambivalent about Marat [27,30], but his contribution to the present topic remains undeniable. Even despite it, though, shadowgraphy was not to appear again officially for another century.

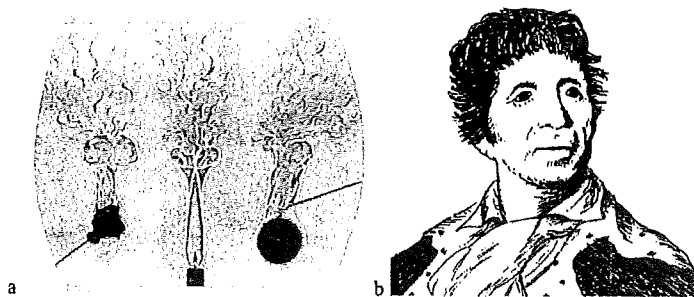


Fig. 1.4. a Marat's drawing of thermal plumes, apparently the first published shadowgram [28] b Jean Paul Marat (sketch by author based on 1793 portrait by Joseph Boze).

1.3 The 19th Century

According to Rienitz [14], the schlieren principle for optical shop testing can be traced from Huygens in 1685 to the optical practice in Paris at the end of the 18th Century. Coincidence or not, it was in Paris in 1859 that yet another prodigy, J. B. Leon Foucault (1819-1868), made the next important contribution to the optics of inhomogeneous media. Foucault is remembered today for his demonstration of the reduced speed of light in water, his invention of the first gyroscope, and especially his great pendulum experiment. Beside these accomplishments his knife-edge test of astronomical telescope mirrors [31,32] seems rather minor, but it was vital to perfecting telescopes and thus, indirectly, to our present knowledge of the heavens.

It is vital here as well, because it is the first use of an explicit cutoff (mask, stop, diaphragm, filter, *knife-edge*), external to and distinct from the pupil of the eye, for schlieren imaging. With this, the discrimination of regular vs. irregular rays occurs independently of the observer. This cutoff is now recognized as the salient distinguishing feature between schlieren techniques and all related approaches.

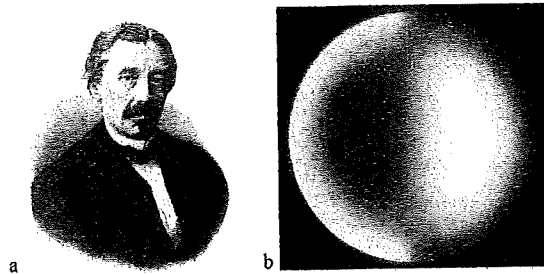


Fig. 1.5. a J. B. Leon Foucault [31], b "shadow" pattern of a parabolic mirror observed by Foucault's knife-edge test (photo by author).

So, although Huygens was the original pioneer of optical shop testing, Foucault's knife-edge test marks the recognized beginning of the field [31,33]. With this simple but exquisitely-sensitive variant of what we now call the schlieren technique, even amateurs could test the figure of their homemade telescope mirrors with sub- μm accuracy. Porter [34] called it "one of the most delicate and beautiful tests to be found in the realm of physics." The "shadow" pattern of a parabolic mirror under Foucault's knife-edge test is shown here in Fig. 1.5b.

A great hobby of amateur telescope making sprang up in the early 20th Century, feeding the ranks of professional astronomers and supplementing their observations. Even today, modestly-priced parabolic mirrors intended for amateur telescopes provide optics for many of the schlieren instruments in the West.

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Like Huygens, Foucault took no apparent notice of any airflows made visible by his knife-edge test, but others did. The Foucault test caught on quickly, and in 1864 Henry Draper [35], an NYU professor and amateur astronomer, published a drawing of the warm air rising from his hand (Fig. 1.6). Draper disliked this, claiming that it "will completely destroy the beauty of an image." Likewise most astronomers, with the exception of Douglass [36], have avoided developing an interest in the atmospheric phenomena that stand between them and the stars.

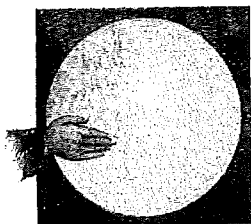


Fig. 1.6. Henry Draper's drawing of the thermal convection from his hand, as observed while testing a telescope mirror.

At about the same time as Foucault – the earlier work of Hooke and Huygens having been forgotten – August Toepler (1836-1912) re-invented the schlieren technique between 1859 and 1864 [3,12]. He had a flair for naming things, and so named his new technique distinctively after optical inhomogeneities in glass, which were known in German as "Schlieren." When his attention was called to Foucault's work, Toepler admitted the similarity but defended his claim of originality. He noted that Foucault was only concerned with testing mirrors, and did not see the broader value of this technique as a powerful scientific instrument in its own right [37,38]. However, the priority issue was clouded enough that journal editors of the time, including Kirchhoff and Helmholtz, were initially shy to publish Toepler's schlieren method. Some French scientists [38] even claimed that Toepler had appropriated Foucault's method and renamed it. Still today the otherwise-universal term *schlieren* is replaced in the French vocabulary by *strioscopie*. The extent of this confusion at the time is well-illustrated by Mach's [39] reference to the schlieren technique as "the optical method of Foucault and Toepler (sic)."

Nonetheless Toepler's argument has stood the test of time. Though he did not invent the knife-edge test, he certainly did invent the schlieren imaging technique and was its first and principal developer, proponent, and patriarch.

³Hans Jebsen-Marwedel [117] has discussed the meaning of "Schlieren" as a word, an object, and a concept. It is, of course, the plural form of "Schliere," whose English equivalents are "streak," "striation," and "cord." (Though the German noun is always capitalized, in customary English usage the capitalization is dropped.) Its etymology connotes slime, ulceration, turbidity and knottiness, all of which can apply, for example, to flaws in glass. Toepler, however, was the first to apply the term to generic optical inhomogeneities. Given the history of the word schlieren, Jebsen-Marwedel concluded that "Toepler's method could not have had a better name than this."

Little was known of Toepler up to the present, though he ranked among the most prominent scientists of his time. Thanks to Krehl and Engemann [12], we now have a clearer picture of the man and his fascinating scientific career. Briefly, he was born in Brühl, Germany in 1836, and showed an early aptitude for art, music, and science. By age 23 he was already a popular lecturer in chemistry and physics at the Agricultural College of Poppelsdorf (now part of Bonn), and an innovative researcher. During a 5-year period at Poppelsdorf, while earning his Ph.D., Toepler invented, named, and refined his schlieren technique. For the next 15 years he applied the instrument to observe, demonstrate, and publish many diverse phenomena for the first time. The long-neglected optics of inhomogeneous media had finally found a champion.

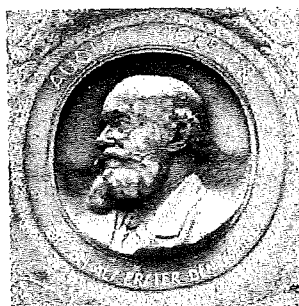


Fig. 1.7. August Toepler's likeness from his tomb in Dresden (courtesy of Dr. P. Krehl, Ernst-Mach-Institut). The German epitaph reads "He was the first who saw sound." Actually it was shock waves, not sound, that Toepler first saw using his schlieren method.

Toepler's work on the schlieren technique was collected toward the end of his life and published in two volumes of *Ostwald's Classics of Exact Science* [40,41], which can still be found in research libraries. The first volume reproduces his original treatise [3], which was privately published at his own expense (perhaps due to the priority dispute with Foucault), and which is now very rare. It names and introduces the principle of the new instrument, then proceeds to explore previously-invisible aspects of diverse natural phenomena ranging from flames and convection columns to electric sparks.

Toepler was the first to devise a practical apparatus for schlieren observations (Fig. 1.8), including an adjustable knife-edge cutoff, a lantern light source, and a telescope for viewing the image directly. (Nowadays the telescope is replaced either by a ground-glass viewing screen or a camera.) The long-focus lens combination at the center of Toepler's apparatus was named the "schlieren head," a term we still use. He also described an 8-10 minute procedure to set up and align the apparatus "from scratch." This is not difficult, given a little experience, but it often evades the novice (see Chaps. 7 and 8).

Like his predecessors, Toepler began his schlieren investigations with optical shop testing in mind, but he soon broadened his outlook. For example, he noticed that the convection from his hand produced weak schlieren calling for fine optics and a sensitive knife-edge adjustment. By systematic tests he found that air temperature differences less than 1°C were visible, corresponding to a change in re-

fractive index of only one part per million. There followed studies of gas and liquid mixing, the world's first visualization of the human thermal plume, one of the earliest images of Marangoni convection [37], and even the convective heat transfer from plants. While all these observations are understood by geometric optics alone, Toepler also noted the effect of light diffraction in a forming bright halo about opaque objects in his schlieren image. He understood and promoted this new schlieren technique as if it were his own child.

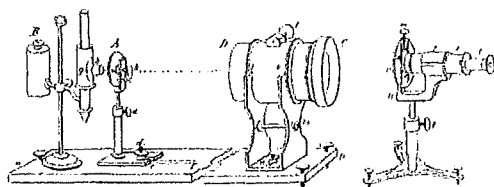


Fig. 1.8. Toepler's original schlieren apparatus [41].

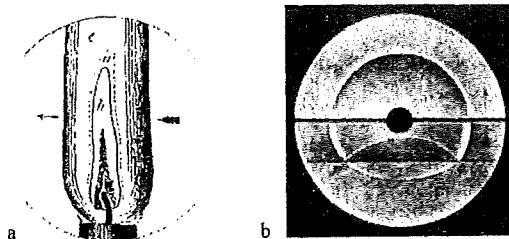


Fig. 1.9. a Toepler's drawing of the schlieren image of a candle flame [40]. b drawing of the schlieren image of a spherical shock wave from an electric spark in air [37].

Photographic media of sufficient speed for schlieren imaging were not yet available in Toepler's era. So, in time-honored fashion he drew his observations by hand. From his extensive schlieren studies a drawing of a candle flame and another of spherical shock wave motion are reproduced here in Figs. 1.9a and b.

Toepler's early efforts to see sound by the schlieren technique failed, but he soon hit upon the use of an electric spark to generate sharp acoustic disturbances. He called these by various names including "sound waves," but they were actually *shock waves* traveling faster than sound [12]. Toepler saw and illustrated the motion, reflection and refraction of shock waves for the first time, thus starting a field of study that is a key element of physics and engineering to this day. 90 years later one reviewer [42] wrote "The shock wave has been one of the most important and popular subjects for study since the discovery of the schlieren effect." One could say that schlieren and shock waves grew up together.

Using a spark gap as a schlieren light source, Toepler observed this shock wave motion with microsecond flashes. He thus shares credit for the invention of

stroboscopic imaging with W. H. F. Talbot (1800-1877) [43], one of the pioneers of photography. Talbot's interest was mainly in portraiture, however, while Toepler's was the first-ever *scientific* use of high-speed imaging. This work inspired Ernst Mach and, later, the modern pioneer of electronic stroboscopy, Harold E. Edgerton (1903-1990) [44]. Thus we see that modern flashlamps of all sorts were, in some sense, sparked by August Toepler.

All of Toepler's 1864 *schlieren* treatise [3] was qualitative, i.e. visual rather than numerical or theoretical. He had an excellent physical "feel" for his subject. For example, he proved the outer mantle of a flame to be convection by duplicating it with a hot metal bulb (as did Marat a century before). He felt the shock wave from a spark in a hand-held cork before he ever actually saw it. Then he demonstrated the dependence of the observed shock motion on the speed of sound by varying the air temperature or composition. As Witting [38] remarked, Toepler's original papers give the student a classical example of physical research: they report practical observations and "building-block" experiments designed to reveal a phenomenon or prove a concept. After the *schlieren* method has done this – which it does superbly – a host of less-general but more-quantitative instruments can be applied to lend numerical values to the details.

Before ending his work on *schlieren*, Toepler turned to microscopy [45]. Here there was already an observation method for transparent objects, called "oblique illumination," but Toepler found it was but a crude version of *schlieren* microscopy. Mounting a variable knife-edge cutoff in the back focal plane of his microscope objective, Toepler demonstrated unparalleled sensitivity, ease of adjustment, and uniformity of field illuminance in the microscopy of transparent objects. Despite this, *schlieren* illumination somehow never assumed a primary role in microscopy and later gave way, along with oblique illumination, to phase contrast and interference methods. That branch of the optics of inhomogeneous media is taken up further in the next section and in Sect. 9.4.7.

Toepler moved on to prestigious university posts in Riga, Graz, and finally Dresden [12]. His other scientific works ranged widely, and included a collaboration with Boltzmann on the physics of hearing [46]. He was famous in later life for these accomplishments, especially his brainchild, the *Toepler schlieren technique*. Eventually an accident and failing health removed him from science at the turn of the century, and he died in 1912 at age 76.

So, two centuries after Hooke introduced it, Toepler succeeded in making a name for the *schlieren* technique. But this time the atmosphere of experimental physics was more receptive, and applications for the new technique flourished. It was quickly recognized as a valuable tool, and was taken up by many scientists of the time, including Ernst Abbe [47], Robert W. Wood [48], Toepler's son Maximilian [49], and especially Ernst Mach (1838-1916).

Mach's is a household name today because, long after his death, the public imagination is captured by high-speed flight and the breaking of the mystical "sound barrier," linked forever to his name. In fact, his name continues to be appropriated for everything from automobiles to computers to razor blades that advertisers want us to associate with speed. The broader picture of Mach's contribution to the philosophy of science is overlooked, and here, as well, the supersonic

flight and shock waves are more to the point. Several excellent articles on Mach's contribution to gas dynamics form the background for what follows [50-53].



Fig. 1.10. Ernst Mach (photograph courtesy of Ernst-Mach-Institut).

Mach's motto, "*Sehen heißt verstehen*" (seeing is understanding) could be the mantra of modern flow visualization, but it played him false over the atom, whose concept he decried. His philosophy required direct observations of nature in order to maintain honesty and realism in scientific theory. When he heard of Toepler's new schlieren method to see the invisible, it must have appealed to him immediately.

In his 30's and holding the Chair of Experimental Physics at the German University of Prague, Mach had both the tools and the talent to pursue the key physics problems of the late 19th Century. Moreover, he had great intuitive skill with experiments, he paid attention to what others were doing in the field, he kept detailed notebooks, and he was always thinking.

From roots in physiology, Mach took up acoustics. Initial experiments with soot tracing of "sound" waves from sparks were indirect, and were replaced by direct schlieren observations. However, where Toepler's delay circuits were unreliable, Mach's succeeded. Also by this time photographic plates became sensitive enough to permit spark-illuminated schlieren photography (e.g. Fig. 1.11). Combined, these developments allowed precise wave-speed measurements, proving that the waves from sparks were not mere sound waves, they were *supersonic*.

The speed of sound or acoustic speed, "*a*," was already known for decades to be about 340 m/s. Then Riemann's theory [54] showed, in 1860, that nonlinear waves of finite strength could travel faster than sound. Mach's schlieren observations confirmed this in 1877, and he wrote [55] "...we deal in our experiments with such waves as described by Riemann." Thus the schlieren technique again played a crucial role in establishing the modern field of shock wave physics.

In 1885 Mach and Wentzel [56] recognized that the simple nondimensional parameter V/a (where V is the wave speed) governs the behavior of such shock waves. It took 40 years before Jakob Ackeret [57] suggested that V/a be called the *Mach number* in honor of Mach's contribution. This Mach number is now central to almost all calculations in gas dynamics and high-speed flight, and partly for this reason, every schoolchild now knows Mach's name.

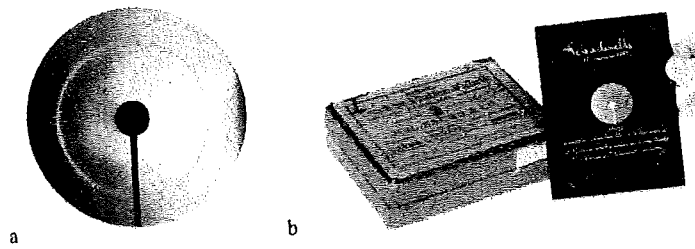


Fig. 1.11. a Mach's Schlieren photograph of a spherical shock wave from an electric spark, b corresponding original negative plate bearing the confusing title "Schallwelle" (sound wave). Photographs courtesy of P. Krehl, Ernst-Mach-Institut.

The reason also has a lot to do with ballistics. Mach took an interest in 1881 after he heard the Belgian ballistician Melsens [58] present a suspicious description of high-speed projectile motion. Mach doubted Melsens' explanation, and had the tools at hand to test it: μ sec spark illumination, delay circuitry, and the schlieren technique. Much of the experimental work was done by his colleague, Prof. Peter Salcher of the Naval Academy in Fiume, Austria, a former student Toepler. Salcher used a rifle known to propel a bullet at supersonic speed. The remarkable schlieren result [4], Fig. 1.12, shows the swept bow shock, tail shock, and turbulent wake of the bullet. Here, in a series of schlieren images, the secrets of supersonic flight were first revealed. This began the field of supersonic aerodynamics, where seeing has been the key to understanding ever since.

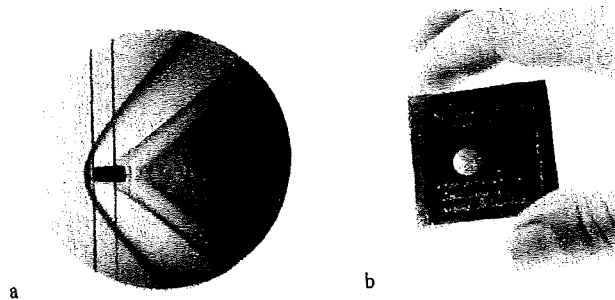


Fig. 1.12. a Mach and Salcher's schlieren photograph [4,59] of the oblique shock waves about a supersonic bullet b Original negative plate with 5-mm-diameter image. Photographs courtesy of P. Krehl, Ernst-Mach-Institut.

Salcher then suggested to Mach [60] that they check their results by observing a supersonic airstream flowing over a fixed projectile. The experiment was done by exhausting the compressed air supply of a torpedo factory through a converging

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nozzle and photographing the result with a schlieren system. One of the resulting images is shown in Fig. 1.13, the first photograph of a supersonic jet ever taken. This experiment also marks the prototype of the *supersonic wind tunnel*, later crucial to advancing high-speed flight.

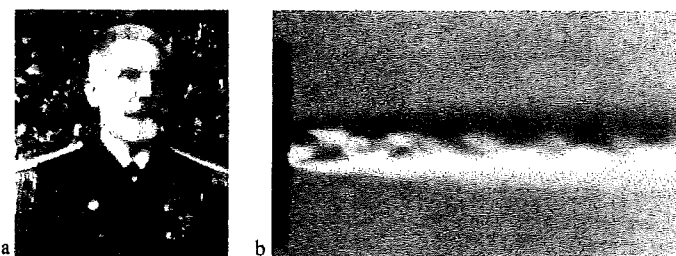


Fig. 1.13. a Peter Salcher (1848-1928), courtesy Dr. G. Salcher, Hermagor, Austria. b the first schlieren photograph of a supersonic jet [60]. Photos taken a century later can improve upon it only by virtue of better photographic media.

Irregular shock wave crossings in the jet were dubbed "Lyra" by Salcher, but later came to be called "Mach disks." In fact, the experiments were done entirely by Salcher, who coordinated with Mach only by mail. Though Mach provided scientific guidance, recent correspondence discovered by Krehl [61] shows that Salcher's contribution has been underrated. If there is anything left to name in gas dynamics, we should name it for Peter Salcher.

The beginnings of unsteady gas dynamics and supersonic aerodynamics by Mach and Salcher thus depended critically on the schlieren technique. Shock waves, ballistics, supersonic jets, and high-speed wind tunnels were soon to follow. Schlieren first achieved its potential here, in revealing the physical phenomena that led to jet and rocket propulsion, high-speed air transportation, and of course a host of deadly military weapons.

One of Mach's assistants in Prague was Vincenz Dvorák (1848-1922), who later became professor of Physics at the University of Zagreb [12,53]. While he worked with Mach, Dvorák published the first *traditionally-recognized* account [23] of the simple visualization method we now know as the shadowgraph technique (Hooke's and Marat's precedents having been forgotten). Dvorák once again used sunlight focused on a 1-mm aperture to project a diverging light beam across his darkened lab onto a white wall. Refractive phenomena in the middle of the beam appeared as shadows on the wall. The similarity to Marat's forgotten "helioscope" shadowgraph apparatus [28] is remarkable.

Dvorák described many observations, including mixing phenomena in water and the atmosphere, the warm convection from a hand, and electric sparks. In fact, he repeated most of Toepler's original visualizations in order to show that similar results could be had by the simpler means of shadowgraphy.

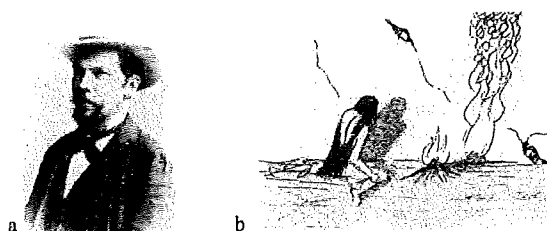


Fig. 1.14. a Vincenz Dvorák (1848-1922). b prehistoric shadowgraphy (sketch by author).

Yet, with due respect to Dvorák, he lacked Toepler's broad feeling for his subject. He attempted no more than a cursory optical analysis of his technique and showed no shadow photographs, though he had the resources to take them. He also made his discovery an adversary of the schlieren technique, claiming the latter was too complex and expensive and had a too-small field of view. That is not the way it worked out: nowadays schlieren and shadowgraphy are complementary tools. Others [2,62] later clarified that shadowgraphy produces no focused image like schlieren, but merely a shadow, hence it is purely a qualitative tool.

Neither did Dvorák coin the term "shadowgraph," but rather called it only "a new, simple form of schlieren observation." It is not actually a schlieren technique, however, since that requires a knife-edge cutoff and the formation of a real image. Boys [62] published the first shadowgraph *photos* in 1893, a few years after Dvorák and a century after the assassination of Marat. Schardin [1,2,63] named Dvorák's approach the "simple" or "direct" shadow method, which it is still called. The term "shadowgraph" seems to have been first used in this context by Townend [64] in the early 1930's, and was then in common use within a decade [65]. Weinberg [66] rounded out the terminology by naming the record produced by the shadowgraph technique: a "shadowgram."

Despite this official history, shadowgraphy is so simplistic that it must have been observed since ancient times (Fig. 1.14b). Wherever sunlight casts a shadow through disturbed air or water, as Hooke [14] noted, a shadowgram is formed. Rienitz [11] also points out that Augsburg optician Johann Wiesel (1583-1662) used the shadowgraph principle in an instrument for self-examining one's eye, pre-dating even Hooke's shadowgraph observations.

Following Dvorák's publication on shadowgraphy [23], as the 19th Century drew to a close, a London amateur microscopist named Julius Rheinberg (1871-1943) devised a schlieren approach to optically "stain" objects in a microscope [67]. Chemical staining was already used to distinguish transparent objects from their surroundings, but it was messy and it could misrepresent or kill biological subjects under study. Rheinberg saw the value of color contrast to enhance microscopy, and placed color filters in the substage diaphragm of his microscope to color-code the light diffracted by the structure of his subjects. This is the color analog of Toepler's [45] black-and-white microscopical schlieren method, though nothing indicates that Rheinberg knew of Toepler's prior work.



Fig. 1.15. Julius H. Rheinberg (1871-1943). (Photo courtesy of Peter Rheinberg, Graticules Ltd.)

Rheinberg illumination is still used today, a century later, to produce brilliantly-colored microscopic images that are obviously also schlieren images to the trained eye (see Color Plate 1). It reached its zenith in 1933 when Zeiss produced the "Mikropolychromar" microscope illuminator based on Rheinberg's principle [68]. More recently, Rheinberg illumination was eclipsed by differential interference color contrast, but it is still used by a few microscopists with outstanding results.

However, Rheinberg's discovery was broader than this fate implies. It was apparently one of the first uses of color filters in any sort of optical imaging system. It thus set the stage for color schlieren methods (Sect. 5.2) as well as for modern methods of pseudocolor-encoding grayscale images [69], white-light optical processing, and a variety of applications eventually including color television projectors [70]. In principle, Rheinberg's approach encodes information in a white-light image projector by way of the azimuth angle θ , measured in a plane perpendicular to the optical axis. This was named " θ -modulation" decades later [71], and became the basis for the modern field of white-light optical processing [72].

Like his work, Julius Rheinberg was himself equally interesting [73]. At age 24 his microscopy brought him together with Ernst Abbe of the Zeiss optical works in Germany, the father of the modern microscope. At the outbreak of World War I, Rheinberg and his brother Ernest were called upon by the British government to manufacture optical sights and eyepieces formerly obtained only from Germany. Julius coined the term *graticules* for these items, which now appears in the Oxford Dictionary. The firm of Graticules Ltd., now directed by Julius's grandson Peter Rheinberg, thrives to this day in Tonbridge, outside London.

1.4 The 20th Century

Early in the 20th Century, schlieren imaging caught on in the leading experimental physics labs around the world due to the publications by Toepler, Mach, and colleagues. In the US, physicist Robert W. Wood (1868-1955) [74] used it to explore shock wave motion in the air, while in Germany it became a key tool in the lab of the world's leading fluid dynamicist, Ludwig Prandtl (1874-1953).

Prandtl [75] and some of his students at Göttingen University took an interest in supersonic gas flows about the same time that, elsewhere in the world, powered human flight was just beginning. This interest was tweaked by an unlikely application, though: sawmill dust collectors. Theodor Meyer, Prandtl's student, derived the theory of oblique waves in supersonic flows in his 1908 Ph.D. thesis [76] while Ernst Magin [77] made schlieren observations of them. These images are so well-suited to illustrate the phenomena that they are still used today (Fig. 1.16).

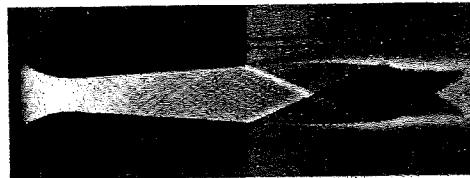


Fig. 1.16. Supersonic nozzle flow pattern photographed in Prandtl's lab [75,77].

Also at the beginning of the 20th Century, the field of ballistics was coming into its own. The world's expert ballisticians were also German: Dr.-Ing. Carl Cranz (1858-1945). As Professor of Ballistics in Berlin, he authored a famous textbook on the topic [78] and trained two generations of students [79]. Given the importance of schlieren to his work, Cranz visited Ernst Mach in Vienna in 1907 to learn more [80]. Subsequently Cranz and his students applied the schlieren technique and high-speed cinematography to bullets in flight, first at 5,000, then 100,000, and finally more than a million frames/second [81].

In this manner the schlieren legacy of Toepler and Mach was handed over by Cranz to his star student, Hubert Schardin (1902-1965). Schardin became Cranz's assistant in 1927 at the Berlin Technical University in Charlottenburg. Cranz was already 69 but still vital. He and Schardin made a crucial contribution to high-speed photography: the multi-spark camera now known as the *Cranz-Schardin camera* [6]. Using shadowgraph or schlieren optics, having no moving parts, and forming up to 24 separate images on a single photograph, this camera enabled the high-speed imaging of physical phenomena at more than a million frames/second – far faster than any other high-speed camera available at the time. With this camera many important studies of explosive events, shock-tube flows, and ballistic impacts were later carried out by Schardin and his colleagues. It became the premier instrument of German ballistics, and is still used 70 years after its invention.

But much more of this history revolves around Hubert Schardin. His 1934 Ph.D. thesis is entitled "The Toepler Schlieren Technique – Principles for its Application and Quantitative Evaluation" [1]. This work provided, for the first time, a solid theoretical background for schlieren imaging. In his early thirties, Schardin was already well on his way to becoming the 20th Century patriarch of high-speed physics and the optics of inhomogeneous media [79].



Fig. 1.17. a Hubert Schardin (1902-1965), b three frames from a Cranz-Schardin-camera schlieren sequence of a blast wave striking a model building (courtesy Ernst-Mach-Institut).

According to Kutterer [80], Schardin learned from Cranz and other professors at Berlin the art of extracting the solution of a difficult technical problem by the simplest-possible means available. This is the clear influence of Toepler's and Mach's school of experimental physics, described earlier. Today, alas, in an age of massive computer power applied to almost everything, this is a lost art.

From Cranz's retirement in 1935 until the end of World War II, Schardin directed the Ballistics and Technical Physics Institutes of the Luftwaffe Technical Academy in Berlin-Gatow. During this period came his second major publication: "Schlieren Methods and Their Applications" [2]. Here we see his mature inventive genius at work in an extensive 136-page monograph, including the almost-casual introduction of several entirely-new schlieren arrangements. (One of these, the lens-and-grid focusing schlieren method to be described in Chap. 4, is only reaching true fruition today.)

Profusely illustrated and including all necessary mathematical rigor, this second key paper of Schardin on schlieren methods [2] is a delight to read. Schardin not only did splendid schlieren and shadowgraphy, but he also had the literary skill to convey his work in comparable style. It includes a section on shadowgraphy, and half of it is devoted to applications spanning a broad range of scientific pursuits. Many of its fine original photographs are reproduced here. Published in German during World War II, it is hard to find today. Nonetheless it has the reputation of the classical reference work [82], and all serious students should read it.

In 1945 Schardin and his research group were caught up in the rift of Germany, and were sought by both the US and France for their ballistics expertise. France made the better offer, and they ended up at Saint-Louis in the French Alsatian region. There, in 1958, Schardin became the first German director of ISL, the German-French Research Institute Saint-Louis, which remains today a world-renowned center for ballistics, shock tubes, and optical flow diagnostics [83]. He also established the Ernst-Mach-Institut in Freiburg, Germany, a sister institute of similar reputation only about 50km from ISL.

Schardin was fascinated by shock tubes, high-speed physics, and color schlieren photography [2] (see Color Plates 2, 9, and 16). He had optical setups in his cellar and attic where his students learned to improvise optical mounts from broomsticks and such [79]. Today a commercial optical mount can cost hundreds of dollars. So, for all of us who ever improvised a knife-edge by a razor-blade taped to a brick, there is comfort in following the footsteps of the master.

Hubert Schardin died of a stroke at age 63, having advanced the knowledge of schlieren methods further than anyone since Toepler. He is remembered for his scientific contributions to ballistics and the physics of all manner of high-speed phenomena, as well as his leadership in defense technology and the establishment of great scientific centers. One of his former students, Reichenbach [79], claims: "Schardin was a researcher and scientist with heart and soul." R. J. North [84] wrote: "Schardin's papers were works of scholarship as well as science. In retrospect they seem as relevant today as when they were written."

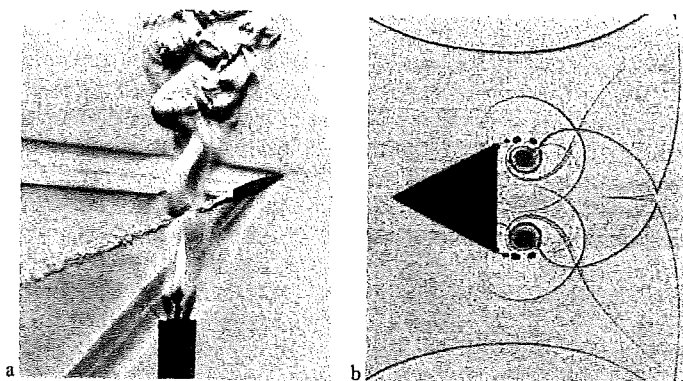


Fig. 1.18. Two famous images by Hubert Schardin. a Schlieren photo of a bullet and a candle flame. b Shadowgram of shock wave diffraction around a triangular block.

During Schardin's lifetime, historical developments were underway that would soon bring schlieren and shadowgraph techniques into far-wider use. There was only a handful of yearly publications on these techniques from Toepler's time up to about 1930; then things began to change. The publication rate increased until the end of World War II, then ballooned to hundreds of papers per year from the 1960's to the present. All told, the publications involving these techniques now number many thousand.

What caused such growth? As we have seen, the optics of inhomogeneous media began in the UK but then moved to Germany. The first application to benefit from this was ballistics, of value primarily to the military. Air power through the end of World War I was too slow to need much optical flow visualization, but this was set to change. As Germany prepared to rearm, rocket propulsion research

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Fig. 1.19. Sonic wind tunnel.

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began in earnest at the Army Experimental Laboratory in Peenemünde. By 1939 a large supersonic wind tunnel was designed by a team led by Rudolf Hermann (1905-1991) and put into operation there [85,86]. Its key instrument was a schlieren system built by the Zeiss optical works. Maximilian Toepler (1870-1960), son of August and then a Professor at Dresden Technical University, advised Peenemünde's wind tunnel instrumentation engineer Heinrich Ramm on schlieren flow visualization [12]. One of the resulting photos of a V-2 missile model under test is shown in Fig. 1.19a. Prandtl also came to Peenemünde, watched the schlieren screen, and ran the wind tunnel repeatedly [85]. A major application for schlieren and shadowgraphy thus arose in wind tunnel testing, and the era of high-speed flight and supersonic warfare began.

The story of German wartime rocketry, the Nazi rain of destruction upon England, V-2 rockets built by slave labor in the Mittelwerk, and the simultaneous dawn of the space age is now familiar [85,86]. Wernher von Braun (1912-1977) and the Peenemünde scientists fled to the West after the war, and eventually played a key role in the US space program. Upon Germany's defeat in 1945, the Peenemünde wind tunnels and schlieren equipment (having been moved to Kochel in Bavaria to avoid bombing) were captured by the Allies. Through the controversial Project Paperclip, the supersonic wind tunnel and its German engineering staff were shipped to the States and installed at the Naval Ordnance Lab outside Washington, DC [85]. There, 22 years later, I had the opportunity – as a student intern – to use this historic test facility (Fig. 1.19b).

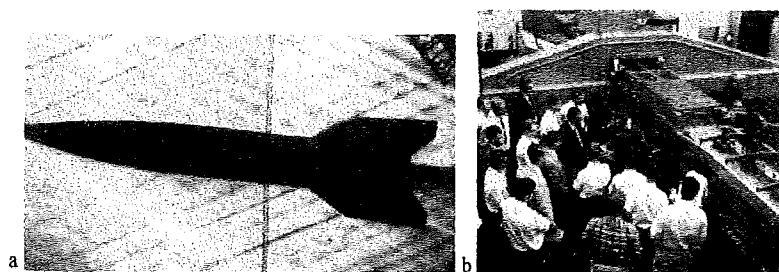


Fig. 1.19. a Schlieren photo of a model of the German V-2 missile under test in the supersonic wind tunnel at Peenemünde. b The wind tunnel itself, with its schlieren system contained in the bridge-shaped enclosure in the background (US Navy photo).

While rocketry was developing in Germany in the early 1930's, American researchers had no such large supersonic wind tunnels. At the Langley Aeronautical Lab of the National Advisory Committee for Aeronautics, they struggled with the knotty problems of transonic airflow. Complex and dangerous flow disturbances appeared when an aircraft approached the speed of sound [87]. Without flow visualization, wind tunnel tests were blind. Eastman N. Jacobs, wind tunnel chief and amateur astronomer, knew about schlieren optics by way of the Foucault knife-edge test. He had a schlieren system installed in 1933. With it, shock waves

20 1 Historical Background

were seen on wing sections even when the initial airflow was subsonic. Schlieren revealed that these shock waves caused boundary layer separation on the wing, akin to stalling the airplane. Efforts began immediately to minimize this problem, if possible, by shrewd wing design [88]. Once again, the schlieren technique provided a crucial glimpse into the Shop of Nature.

Following World War II the emphasis of western high-speed flight research shifted from Germany to the US and the UK. A team of aerodynamicists at Britain's National Physical Laboratory (NPL) continued the struggle over the knotty problems of wing and aircraft design for transonic and supersonic flight. An inspired team of 20 young researchers worked there, with modest resources, under the guidance of Douglas W. Holder (1923-1977). 50 years later, surviving team members still speak fondly of the team spirit and excitement of the time [89-91].

Holder [92] believed in getting at the underlying physics of these airflow problems. Clever use of experimental methods was a key theme of his group's wind tunnel research. Schlieren and shadowgraphy were again crucial in seeing and understanding the complex flows that developed on aircraft wings as the mystical "sound barrier" was approached.



Fig. 1.20. a Douglas Holder (photo courtesy Ramsey and Muspratt Collection, Central Library, Cambridge), b R. J. North (photo courtesy Mrs. Nella North).

Beyond just using these optics, however, R. J. "Jack" North (1921-1998) of the NPL Aerodynamics Division contributed new substance to the techniques. He introduced the graded filter [93] and a simple multicolored filter [94] as alternatives to the standard knife-edge cutoff. The former (Sect. 5.1.1) allows a broad schlieren measuring range and improved clarity, while the latter (Sect. 5.2) brings color schlieren imagery within the reach of everyone. Holder and North also collaborated with the Shell Film Unit to produce a film entitled "Schlieren," [95] that brought the topic to public attention for the first time.

Using North's graded-filter schlieren method and other measurements, Herbert Pearcey studied the flow over transonic wings in an NPL wind tunnel. His work [96] is now a classic in the annals of aeronautics. He proposed wing-section designs that ameliorated the deadly transonic problem known as "shock-stall" [97].

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His “peaky” wing thus allowed subsonic aircraft to fly closer to Mach 1 than ever before. This theme was also taken up by R. T. Whitcomb in the US, leading to what are now called *supercritical* wing sections for efficient transonic flight. Modern commercial jet transports and military fighters depend on this technology. Looking back on this period, Pearcey [90] told me that the success of his research stemmed in large measure from the insight he gained using the schlieren methods of Holder and North.

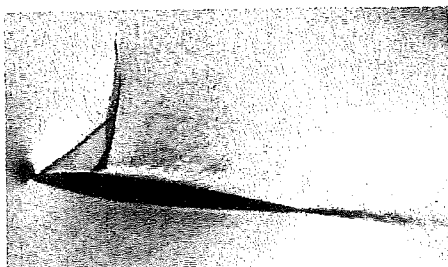


Fig. 1.21. Graded-filter schlieren photo of a 2-D wing section undergoing buffet due to shock-wave induced boundary layer separation, reproduced courtesy of H. H. Pearcey.

In 1963 Holder and North published a small monograph entitled “Schlieren Methods” [98] as part of an NPL series transferring technology to industry. Expanding upon their earlier work [99], it is beautifully illustrated and comprehensive for its size. It surveys the state-of-the-art of schlieren and shadowgraphy in a scholarly manner, and it uniquely covers the practical side of equipment setup, high-speed light sources, and photography of the schlieren image. Along with Schardin’s two papers [1,2], Holder and North [98] is a third classic work that every serious student of the schlieren arts should read.

Douglas Holder left NPL in 1961 to become Professor of Engineering Science at Oxford, was elected Fellow of the Royal Society in 1962, and died too young in 1977. Herbert Pearcey and Eric Rogers are retired from illustrious careers in aerodynamics, and have both contributed to this historical account [89,90]. Jack North contributed too, until his death in 1998. Subsequently Mrs. Nella North has graciously provided additional material (e.g. Color Plate 3).

Another schlieren pioneer, Felix J. Weinberg (1928-) was a Czech teenager at the onset of the Holocaust. He survived the concentration camps at Auschwitz and Buchenwald to later become a world leader in combustion research. His 1963 classic book *Optics of Flames* [66] contains authoritative reviews of both schlieren and shadowgraph theory. He is responsible for naming the shadowgram, and is co-author of the definitive paper on lasers as schlieren light sources [100]. Weinberg’s insights have enriched every chapter of the present book.

While these postwar developments were going on in the West, schlieren and shadow methods followed a similar path behind the Iron Curtain – with some interesting twists. The famous Russian telescope maker D. D. Maksutov (1896-1964) published a book in 1934 entitled “Schlieren methods in the study of optical systems” [101]. However, unlike Schardin in his Ph.D. thesis [1] of the same

year, Maksutov confined himself to optical shop testing of telescope reflectors and refractors. He also introduced the wire or filament cutoff and the exponentially-curved cutoff in the schlieren focal plane (See Sects. 5.1.2 and 10.2.3). The telescope design for which Maksutov is famous came a decade later.

Still later, a Russian book entitled "Shadow Methods" was published in 1968 by L. A. Vasiliev [102]. This 350-page book is the largest tome ever written on the schlieren technique until now. It can be found in English translation in about a dozen US research libraries. While contemporary with Holder and North [98], it is rather different in emphasis (referencing only 137 sources, many in Russian, compared to twice that number in Holder and North). Vasiliev does not spare mathematical rigor, and emphasizes both quantitative schlieren applications and commercial schlieren instruments of Soviet design. Maksutov's hand is seen in the design of the ubiquitous and famous IAB-451 schlieren instrument, which Vasiliev uses as an example (see Sect. 7.4.1).



Fig. 1.22. L. A. Vasiliev (1931-1982). Photo courtesy of Prof. I. V. Ershov.

Though some of the methods Vasiliev explores in depth (e.g. Maksutov's focal filament and curved cutoff) have never found much use in the West, a great deal of useful material is nonetheless found in Vasiliev's book [102]. His talent for clear explanations shines through an excellent translation by A. Baruch. For one already schooled in the schlieren arts, the differing approaches and views from behind the former Iron Curtain are fascinating. I have therefore referred to Vasiliev often in the chapters that follow.

⁴Here a curious confusion between Russian and English terminology needs explanation. Теневые Методы, or *Tenevye Metody* (literally "shadow methods") is a generic term that includes both schlieren (*Shtiren* or *Teplerovski metod*) and true shadowgraphy (*Priamotenevoy metod*). The *schliere* or density nonuniformity itself is *neodnorodnost plotnosti* in Russian. Many Russian authors simply use the term *Tenevye Metody* when referring to schlieren methods, but this is usually translated as "shadow methods," falsely implying shadowgraphy. Dr. A. A. Zheltovodov is thanked for clearing up this confusion.

As for the man himself, Lev Alexandrovich Vasiliev (1931-1982) began his career applying schlieren and interferometer instruments to the gas-dynamic problems of the Soviet space program. He designed several schlieren instruments and his book on this topic [102] became the handbook for a generation of optical scientists in the Soviet Union [103]. He was a Professor in the Moscow Physico-Technical Institute and the author of 4 books, 200 papers, and 30 patents. He died tragically in a mountaineering accident at age 50.

Thus far we've seen several examples of schlieren images and shadowgrams that had a significant impact upon science and technology. A more-recent one demonstrates that this trend is continuing: in 1974, Brown and Roshko [7] published a simple, elegant experiment in which shadowgraphy revealed large coherent structures in the mixing of two planar gas streams. These shadowgrams, one of which is reproduced in Fig. 1.23, spawned a new approach to the understanding of turbulent flows by way of their underlying large-scale structures.

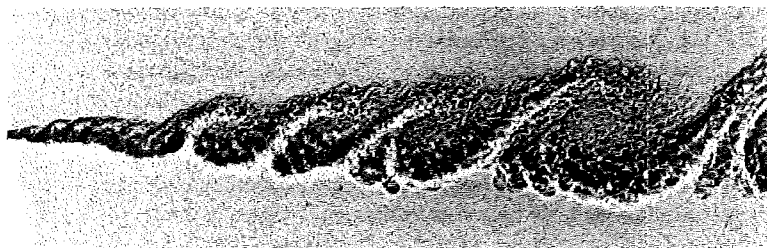


Fig. 1.23. Spark-illuminated "contact" shadowgram of He/N₂ mixing layer (photo courtesy of Prof. Anatol Roshko).

The most-recent history of schlieren imaging concerns novel arrangements for focusing and large fields of view. Ralph Ashby Burton (1925-) wrote his MS thesis on this topic at the University of Texas, Austin, in 1951 [104]. Usually such theses are rather naïve learning experiences, but Burton wrote with authority for a mere 25-year-old. He and several contemporaries independently developed the idea of extended-source schlieren optics that was originally suggested by Schardin [2]. But Schardin overlooked the potential of this approach to yield a large field-of-view, while others [105,106] were chiefly concerned with its sharp-focusing properties. Burton, however, saw large-field-of-view as a fundamental advantage. His work can be found in several publications dealing with schlieren and shadowgraphy in general, and "focusing schlieren" in particular [42,107-109].

Most recently, this theme has been developed further by NASA scientist Leonard M. Weinstein (1940-). Weinstein was an amateur astronomer and photographer as a youth, was trained in physics and engineering, and has been at NASA's Langley Research Center for more than 30 years. There he was involved in high-speed aerodynamics, wind tunnel testing, and instrumentation. Being of an inventive nature, he developed new concepts ranging broadly from instrumentation and

imaging enhancements to solar desalinization of seawater, environmental cleanup techniques, and practical means of space travel.

Around 1990, Weinstein turned his attention to the neglected theme of lens-and-grid schlieren techniques (see Chap. 4). These techniques were never fully developed by Schardin, Burton, or the others who studied them in the mid-20th Century. Weinstein completed the general optical design of these systems and showed them to be more than mere curiosities [110]. For example, on his account several large wind tunnel facilities now use such systems for flow visualization at far less cost than conventional schlieren optics. Applications also abound for the sharp-focusing feature of this approach. More than 70 new schlieren systems have been based on Weinstein's work to date. An August, 1993 discussion between Weinstein and myself led to the world's largest indoor schlieren system, with a field of view of 2.2x2.7 m (see Ref. [111] and Sect. 4.3.5).

Weinstein then had another revolutionary idea: Hooke [17], Huygens [26], and Schardin [2] all observed schlieren against a distant light-dark boundary, but none found much practical use for it. Weinstein realized the potential of this approach with a specially-fitted telescope aimed at the queen of all distant light sources, the Sun [112]. A schlieren cutoff inside the telescope was matched to the edge of the Sun's image and a streak camera recorded a schlieren photograph by scanning the line of schlieren sensitivity across the film. Weinstein demonstrated the practicality of this in 1993, when he photographed a T-38 jet aircraft flying across the face of the Sun at Mach 1.1 and almost 10 km distance from his telescope. The image, shown in Fig. 1.24b, was the largest-scale schlieren image ever captured on film. It was, to say the least, the flow visualization achievement of the decade.

Weinstein's "Schlieren for Aircraft in Flight" is an important new tool for the flight-testing of high-speed airplanes. It was used already for sonic boom research and, more recently, he has adapted a similar approach to rocket-sled testing as well [113] (see Sect. 4.4.1). At the beginning of the 21st Century, Leonard Weinstein's contributions demonstrate that the optics of inhomogeneous media still thrives.

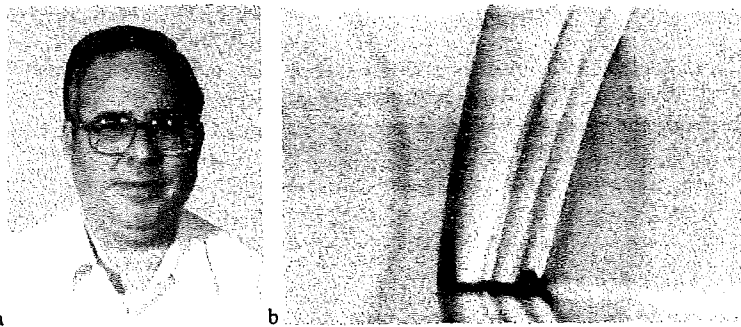


Fig. 1.24. a Leonard M. Weinstein. b Weinstein's schlieren photograph of a T-38 aircraft in flight at Mach 1.1. The vertical scale of this image is about 28 m.